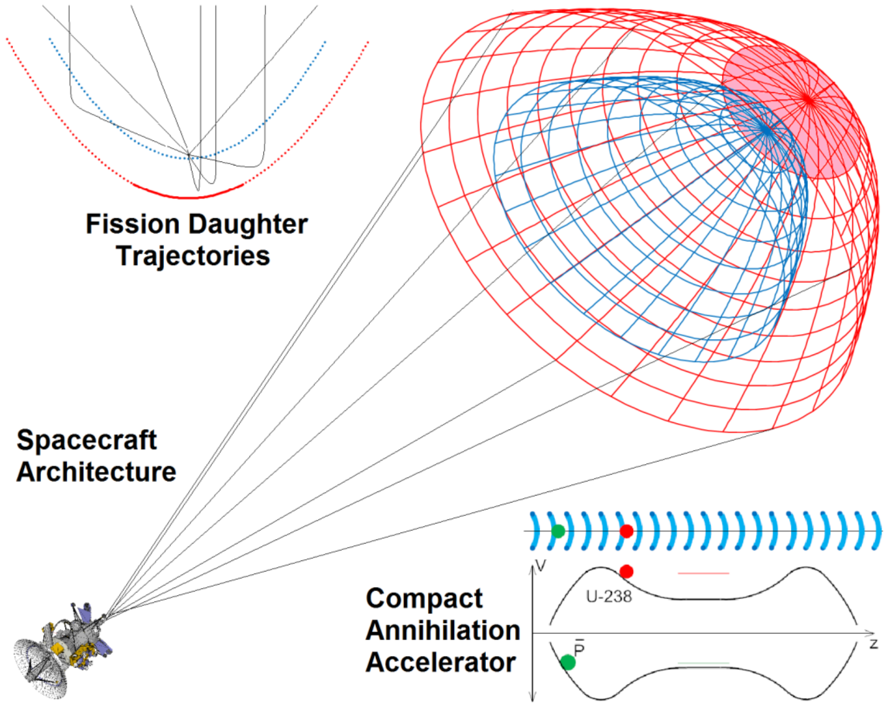
Antimatter-Based Propulsion for Exoplanet Exploration



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HBAR Technologies, LLC
Making Antimatter Matter®

NASA Partner

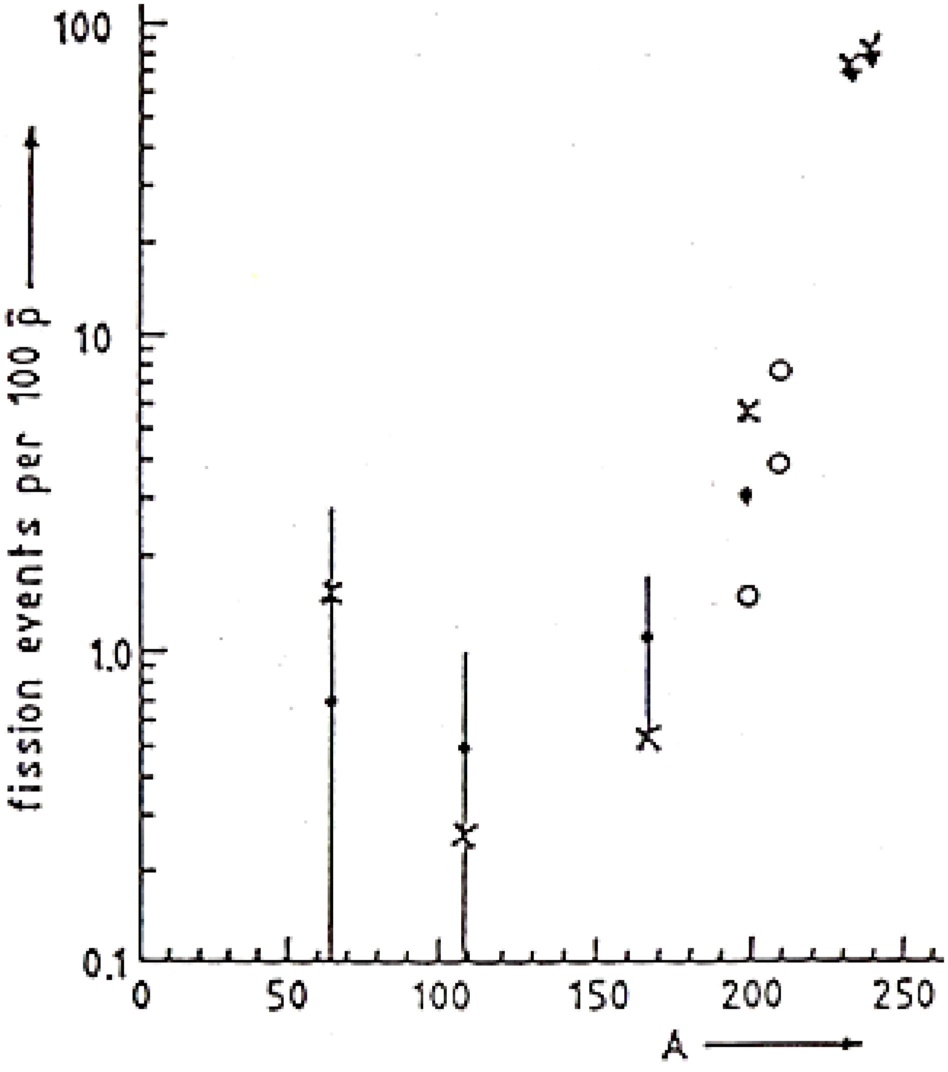
NETS 2021 Track 4

Speaker Introduction

- Ph.D. in accelerator physics at Cornell studying positron-electron collision (1981-86)
- Fermilab Scientist/Project Manager: proton-antiproton collider performance (1986-2000)
- While at Fermilab, concentrated on increasing the production, handling, and storage of antiprotons
- Recipient of the IEEE Accelerator Technology Award and a Fellow of the American Physical Society
- Hbar Technologies, LLC promoting antiproton applications with NIAC, NASA, DOE, and DARPA grants (2002-present)

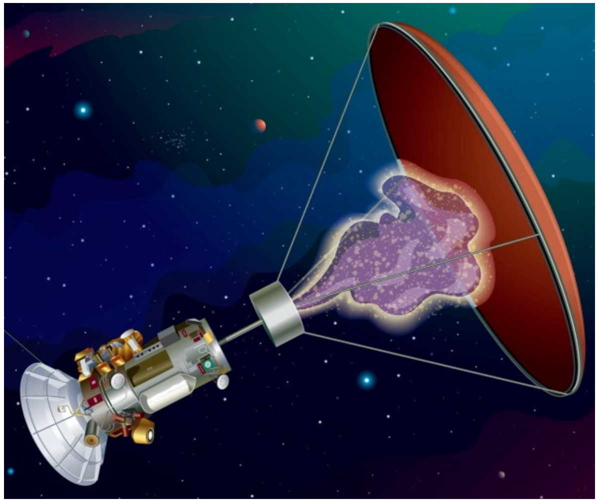
with U.S. Congressman
G. William "Bill" Foster
(IL-14)

Annhilation-Induced Fission



- Almost all annihilations result in fission
- On average two fission daughters each 100 amu are emitted, each with a kinetic energy of 1 MeV per nucleon
- On average each fission daughter has an electrical charge of +20
- These two fission daughters produce the rocket thrust

Antiproton Propulsion System: 2017 and Before



- Started work on this architecture in 2002 funded by NIAC
- U238 sail with antiprotons annihilating on the surface

+ Lightweight and simple

– Inefficient
  1. No fission daughter focusing
  2. Only one daughter emitted per fission
  3. Limited dry mass to fuel mass ratio

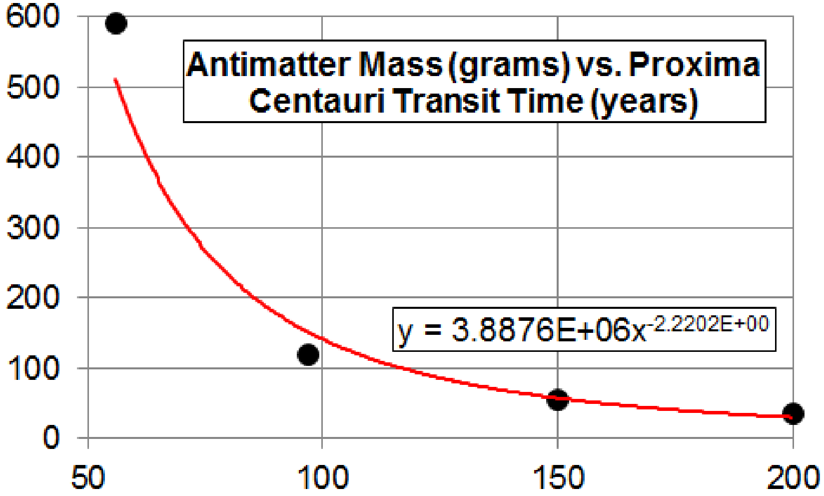
- Long-lived antimatter storage had not yet been innovated

Optimum Spacecraft Cruise Velocity

Historically, there are many projects that have taken >200 years to complete

Proxima Centauri Transit	56 Yrs	97 Yrs	150 Yrs	200 Yrs
Spacecraft Speed	0.1c	0.05c	0.0306c	0.0225c
Deceleration Burn Duration	10y	10y	10y	10y
Spacecraft Dry Mass	10kg	10kg	10kg	10kg
Fuel Mass / Dry Mass	14.1	2.9	1.3	0.84
Antiproton Beam Current	180mA	37mA	17mA	11mA
Propulsion Power	40MW	8.2MW	3.7MW	2.4MW
Propulsion Thrust	4.9N	1.0N	0.45N	0.30N
Total Antiproton Mass	**590g**	**120g**	**54g**	**35g**

- We have developed an antimatter factory that produces 20g/yr for an theoretical annual operational cost of $670 million
- Minimizing the required antimatter mass is important.
- The antimatter mass scales roughly as the square of the spacecraft cruise velocity.



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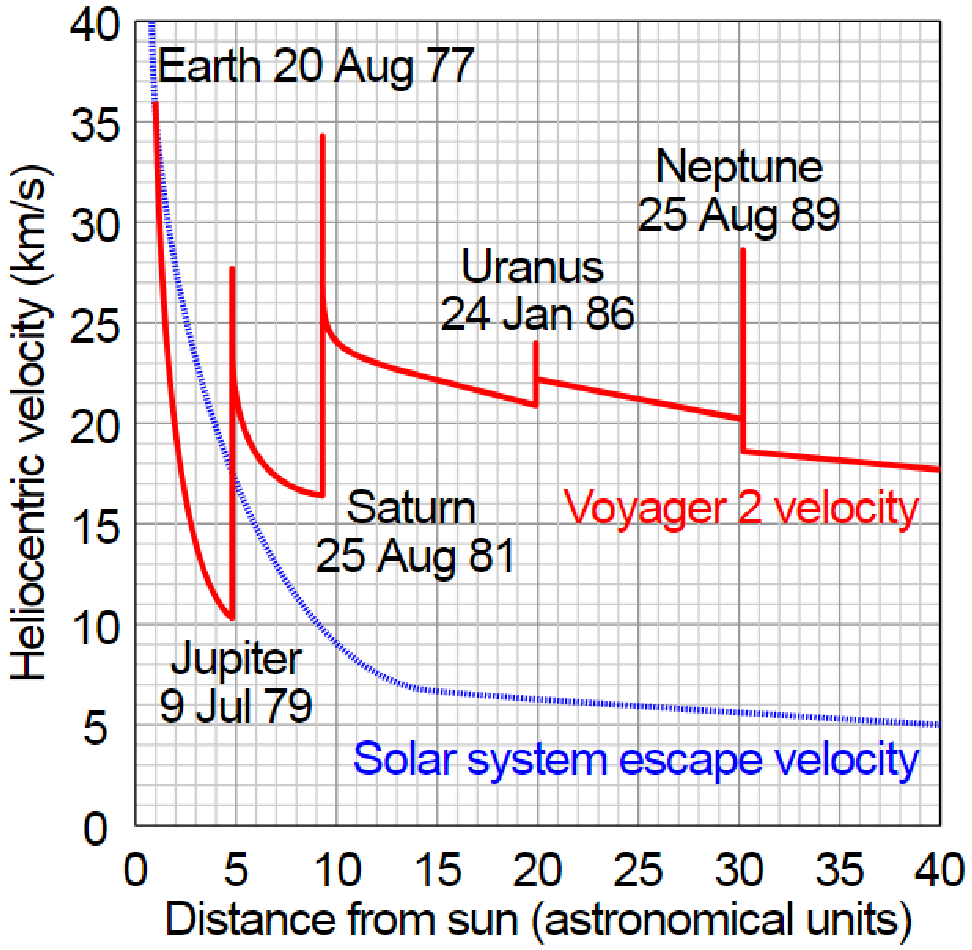
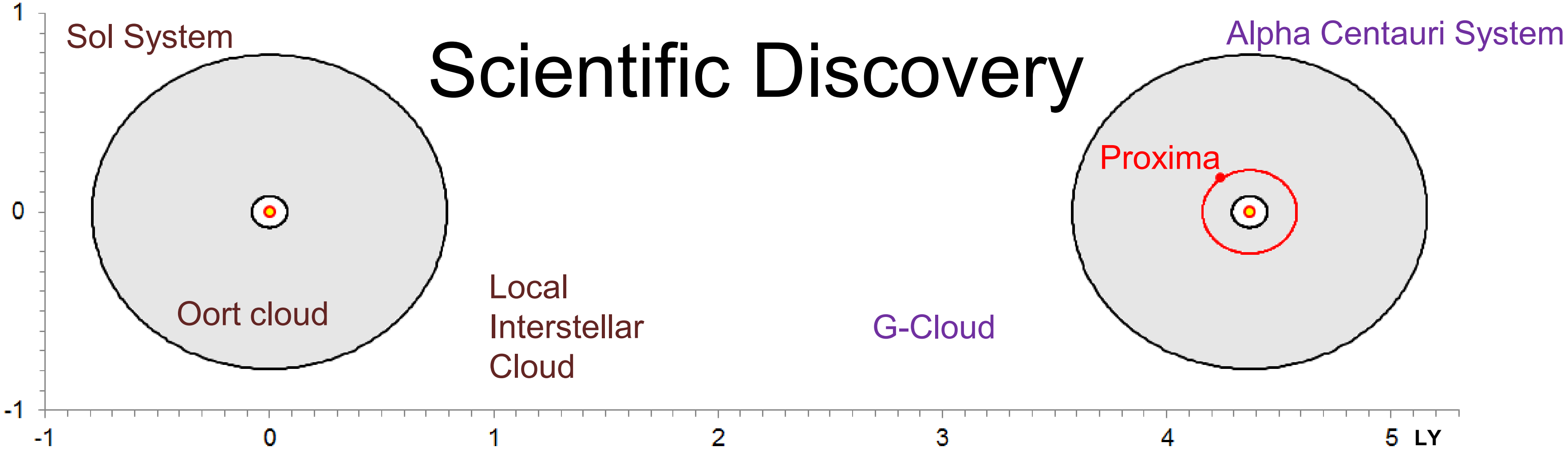
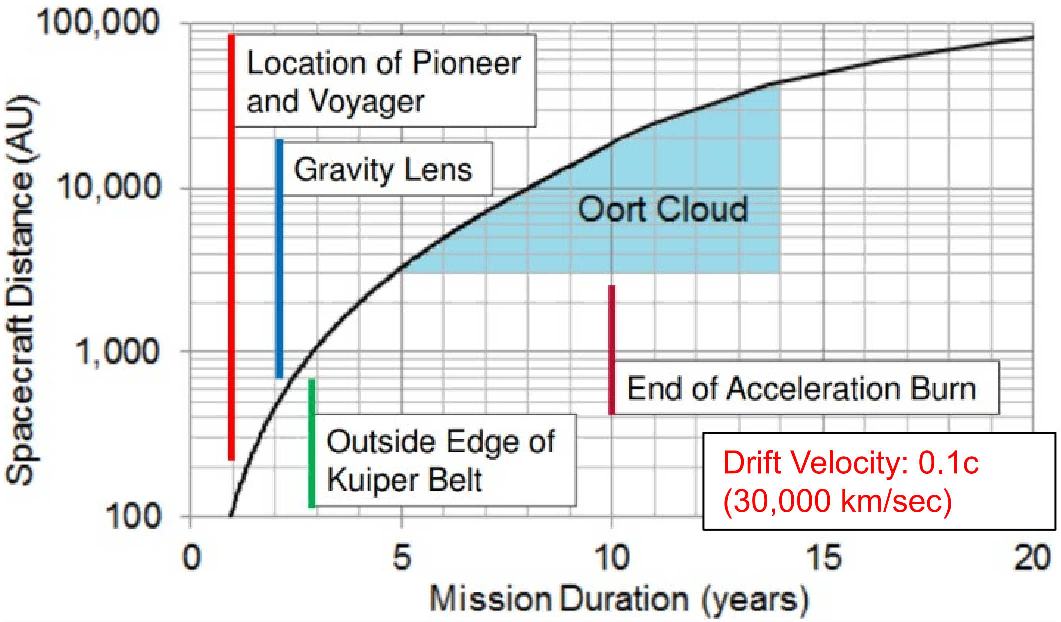
Historical Analogy: Voyager 2



- The primary purpose of Voyager 2 was to visit four of the outer planets, a mission architecture that took 12 years.
- 30 years after Neptune the probe (at 120 AU from the Sun) provided measurements of the heliopause.
- Voyager 2 would not have been approved by NASA if the only justification was the heliopause measurements over 40 years after launch.
- Similarly, a mission to Proxima b is unlikely to be approved unless its architecture includes early and robust scientific discovery.

Scientific Discovery





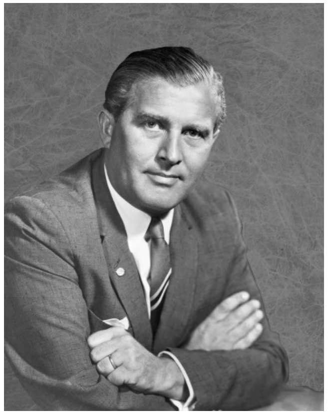
1) Heliopause: Year 1
2) Kuiper Belt: < 3 Years
3) Sol Oort Cloud: Years 5-14
4) Local Interstellar Cloud
5) Interstellar Magnetic Field
6) G-Cloud
7) Centauri Oort Cloud
8) Stage1: AB system flyby
9) Proxima b orbit

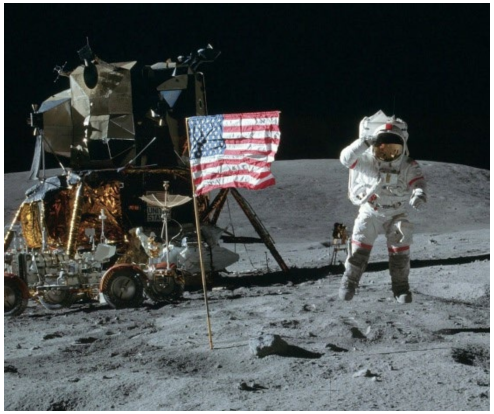
Mission Architecture

- The interstellar portion of the spacecraft is composed of two stages:
  1) Acceleration stage that subsequently performs a deflection burn toward a flyby through the Alpha Centauri AB binary star system after separation from the …
  2) Deceleration stage that bring the 10 kg instrument package into orbit around the habitable zone exoplanet Proxima b, providing decades of maneuvering propulsion and plentiful power for scientific discovery and robust data transmission back to Earth.
- The propulsion and power systems are based on antimatter-induced nuclear fission of depleted uranium.
- Both stages are capable of deploying up to 1000 gram-scale chipcraft to perform auxiliary measurements during the interstellar voyage and at Proxima b. These chipcraft are envisioned to have a <0.2 AU operational range from their respective stages.
- Both stages are tasked with performing robust scientific discovery measurements within a few years of the beginning of the mission.

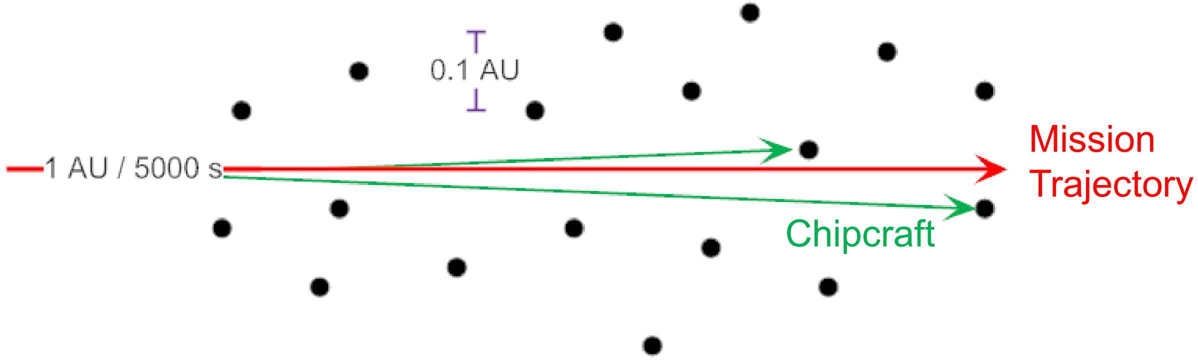
Historical Parallel: Apollo Moon Landing

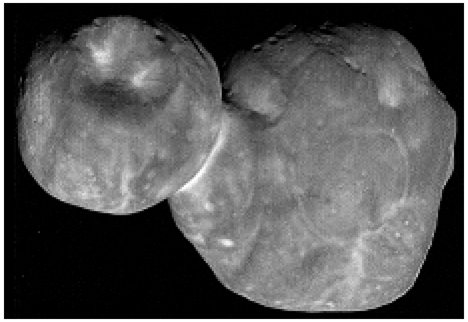
- The lunar landing occurred in 1969. The enabling technologies were rocket staging, liquid fuel rocket motors, and missile guidance systems
- President John F. Kennedy set the goal in 1961 **(T -8 years)**
- Werner Von Braun: World War II development of the V2 and post-War work in Huntsville, AL **(T -20 years)**
- Robert Goddard: Patented staging and liquid fueled rocket in 1914 **(T -55 years).** Also worked on gyro guidance



Discovery Example: Oort Cloud Object Flybys

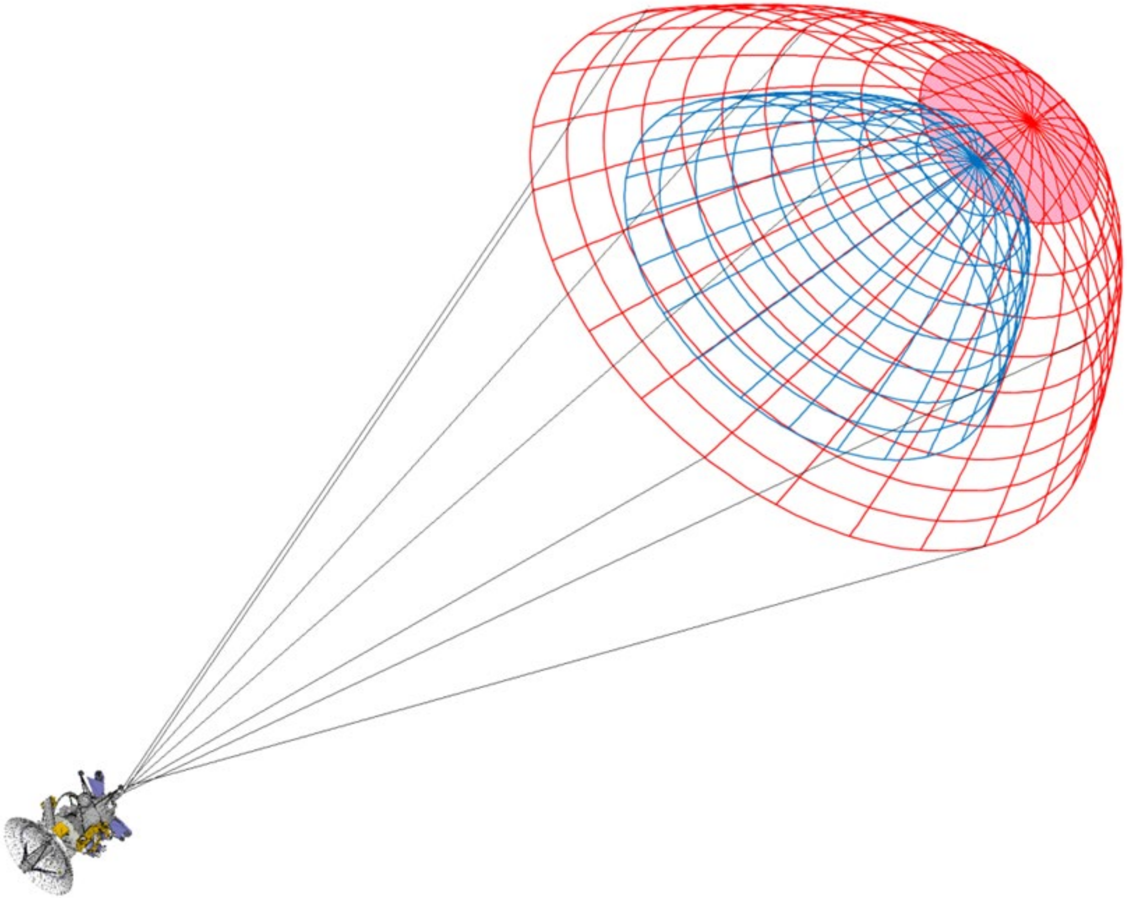




New Horizons flyby of Arrokoth

- According to some Oort cloud models, the average separation of kilometer-scale Oort cloud objects is approximately 0.1 AU.
- Within a cylindrical volume 0.1 AU in radius, on average the spacecraft passes 3 objects every 100 AU, or one object every other day. This represents an available sample size of approximately 1,200 objects within the Sol Oort cloud.
- Gram-scale chipcraft (envisioned by Starshot Breakthrough) are used to perform close flyby observations of (or impacts into) these objects, relaying data to the main spacecraft for subsequent transmission back to Earth.
- The Problem: While the communication laser has sufficient power to perform a LIDAR scan of such objects, detecting the proximity of these objects requires a passive sensor approach (i.e. stellar occultation, electromagnetic emission, etc.)

Antimatter-Induced Propulsion



Antiproton Propulsion System: 2018 and Beyond

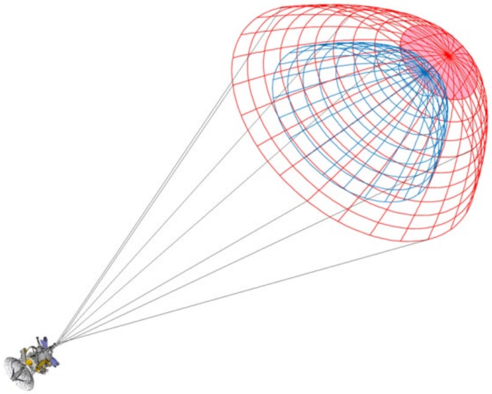
- Modified architecture while applying to NIAC in 2018
- U238 ions interact with antiprotons in a lightweight electrostatic trap

\+ Lightweight electrostatic nozzle

– More complicated U238 fuel and antiproton delivery methods

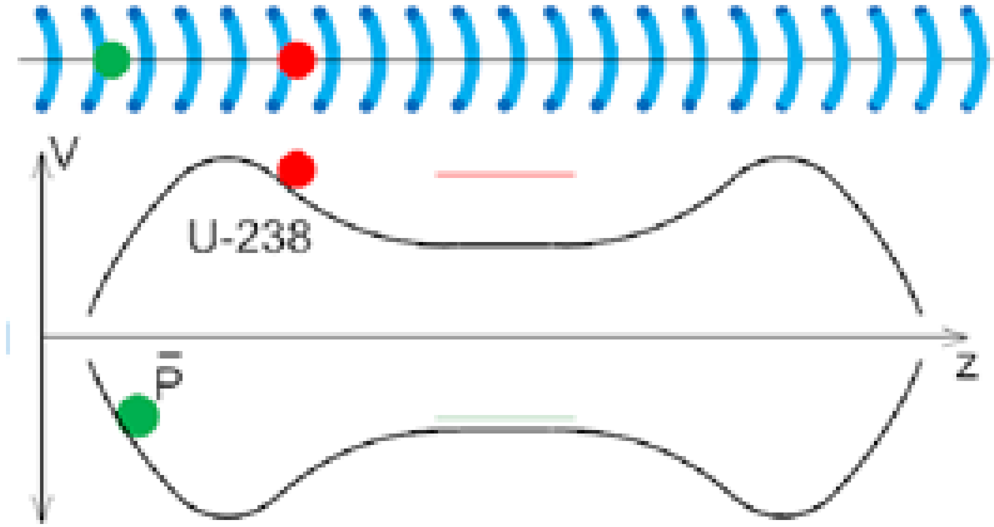
\+ Much more efficient

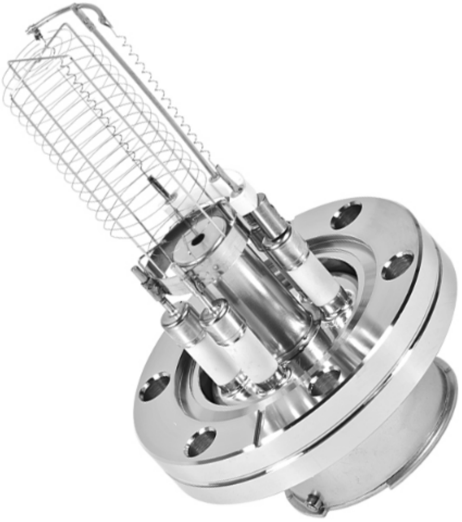
1. Charged fission daughter are focused
2. Both daughters emitted per fission
3. Unlimited dry mass to fuel mass ratio



- Long-lived antimatter storage has been solved!

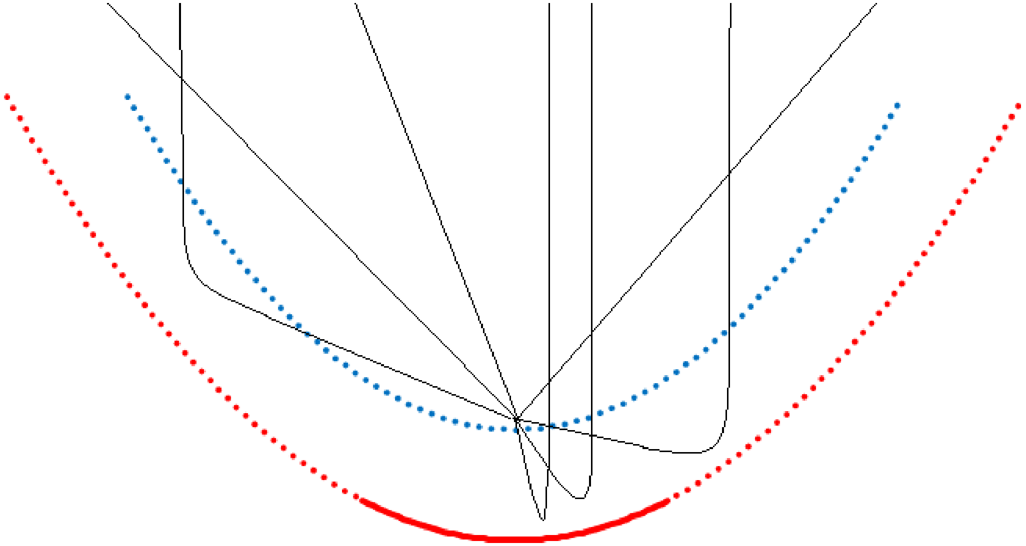
Depleted Uranium Annhilation





- A lightweight electrostatic trap can store a negative antiproton beam and a singly-ionized U238 beam as long as they are in longitudinal motion (classic strong focusing)
- dE/dx slows antiprotons with respect to U238 nuclei, enhancing annihilation probability
- Architecture allows almost all fission products to escape

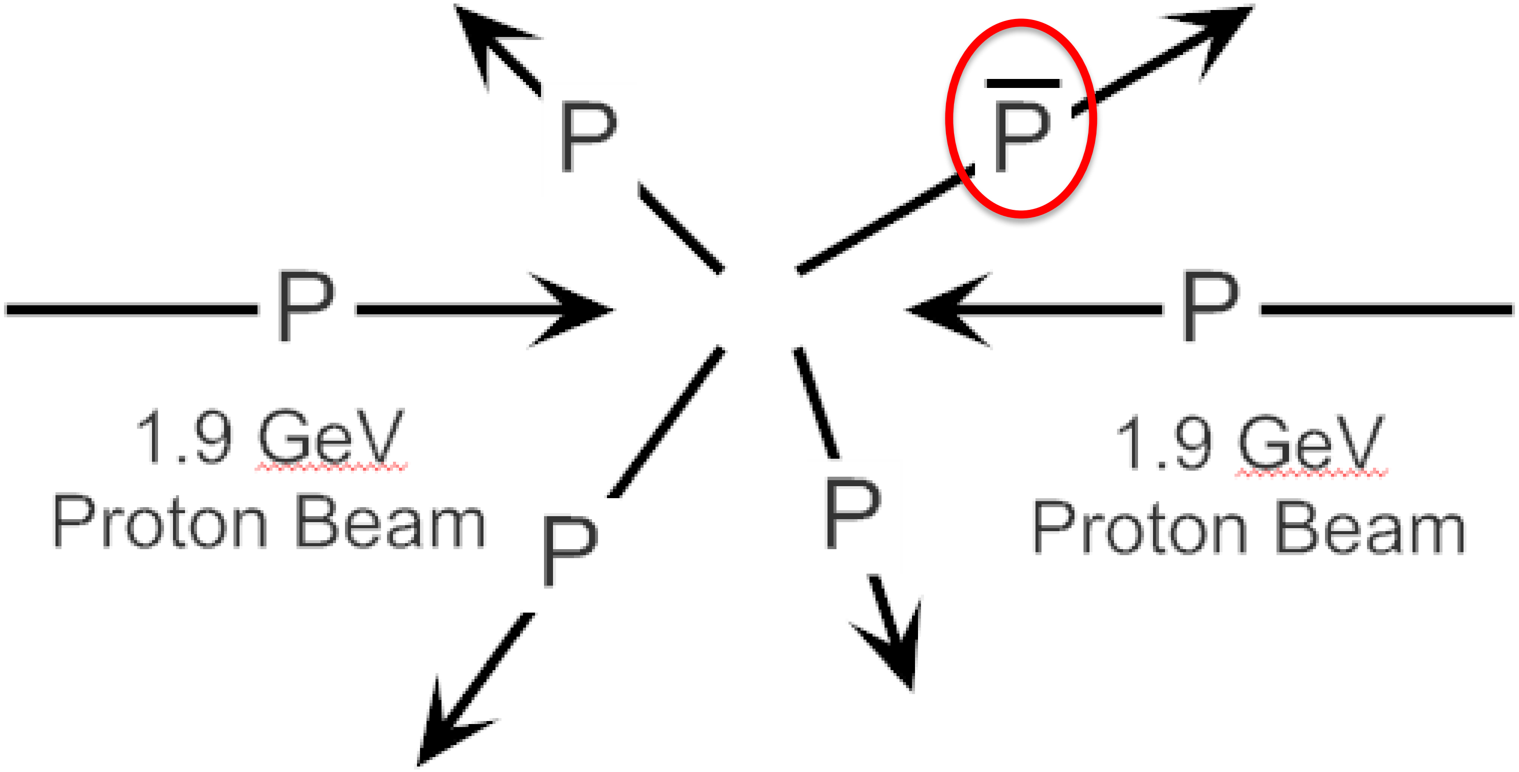
Thrust Collimation and Electrical Power



Electrostatic fission daughter collimation is accomplished by two lightweight charged wire-mesh electrodes: **Outer Mesh** is positively charged wrt to the **Inner Mesh**.

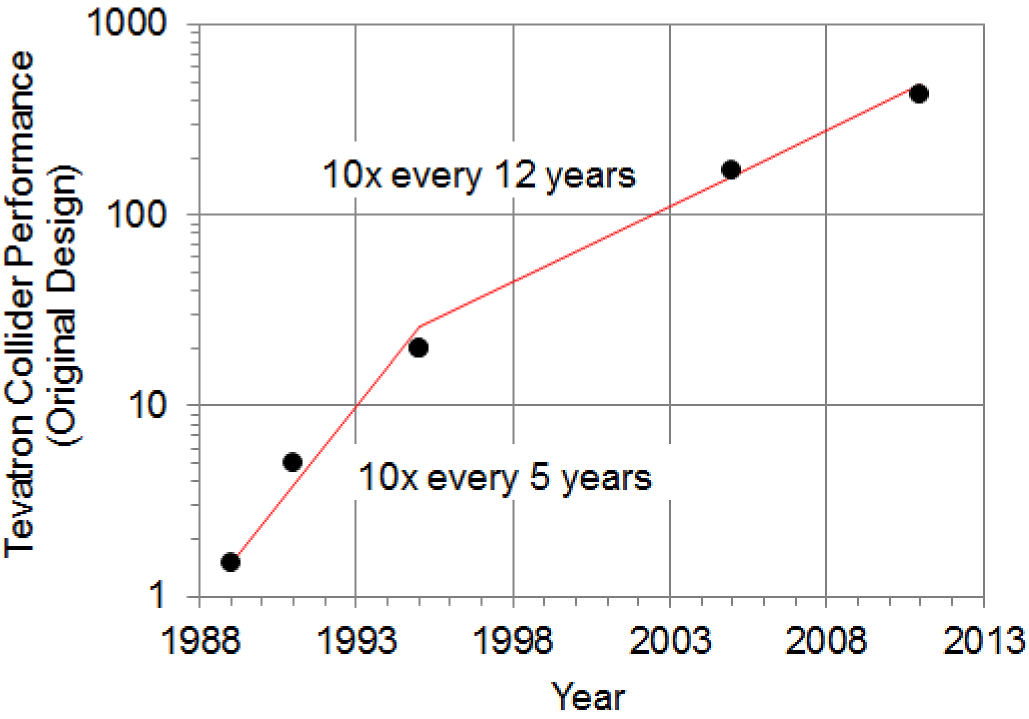
- Voltage between electrodes is adjustable up to 5 MV
- Thin foil near apex of the **Outer Mesh** intercepts charged fission daughters (electrical current) to produce onboard electrical power
- Electrodes are shaped to provide fission daughter collimation: maximum longitudinal momentum transfer

Enhanced Antiproton Production



Fermilab Antiproton Production (1986-2011)

Peak Production Rate of 2 nanograms per year



Change in Slope: Civil Construction & Financial Scale

My Tenure at Fermilab: 1986 through 2000

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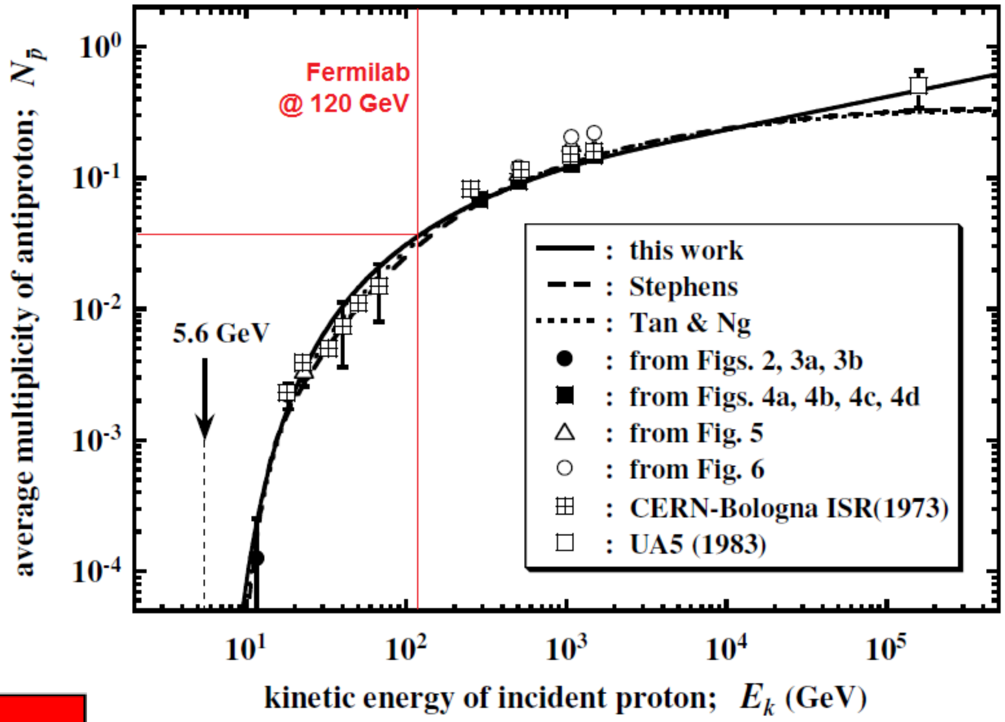
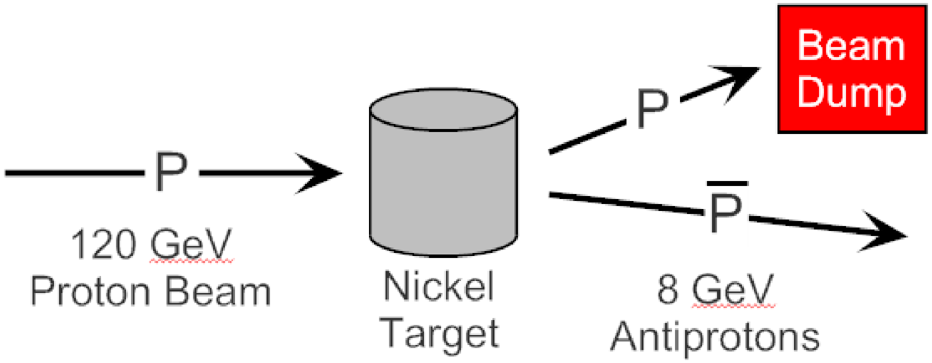
Enhancing Antimatter Production

- The dominant technical risk associated with antimatter-based deep-space propulsion is the production of sufficient antimatter.
- There are 3 basic improvements needed to increase production from 2 ng/yr to 20 g/yr (a 10-fold enhancement).
    1. Antiproton Production
    2. Antimatter Accumulation
    3. Antimatter Storage

Fermilab Antiproton Production Method

- Thick target decelerates protons before antiproton production
- Thick target absorbs and scatters exiting antiprotons
- Only about 1/3 of the protons interact with nuclei, 2/3 only produce heat



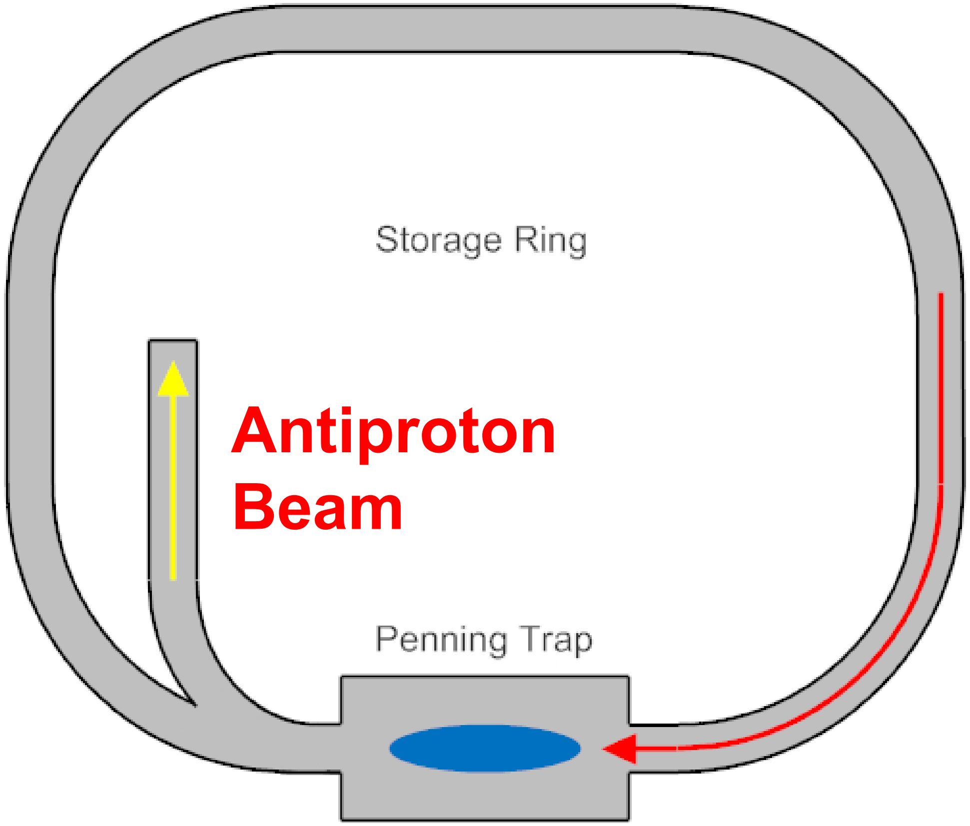


$$P + P \longrightarrow P + P + P + \bar{P}$$

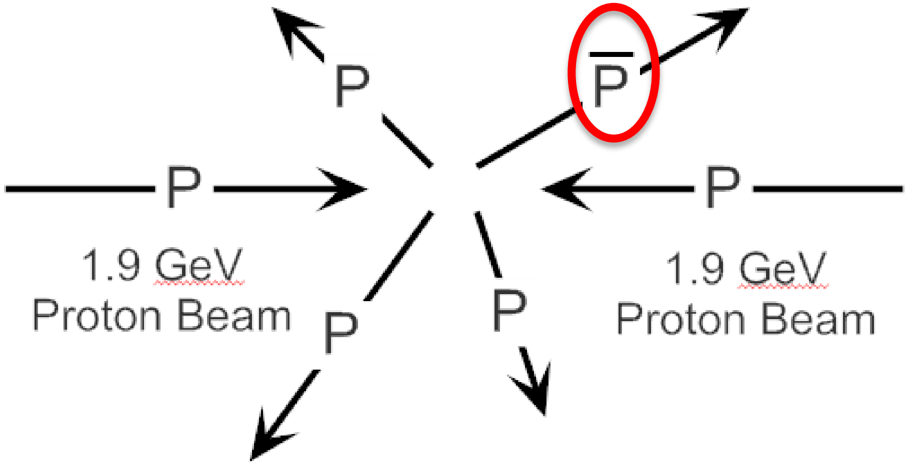
This method is highly optimized for colliding particle physics

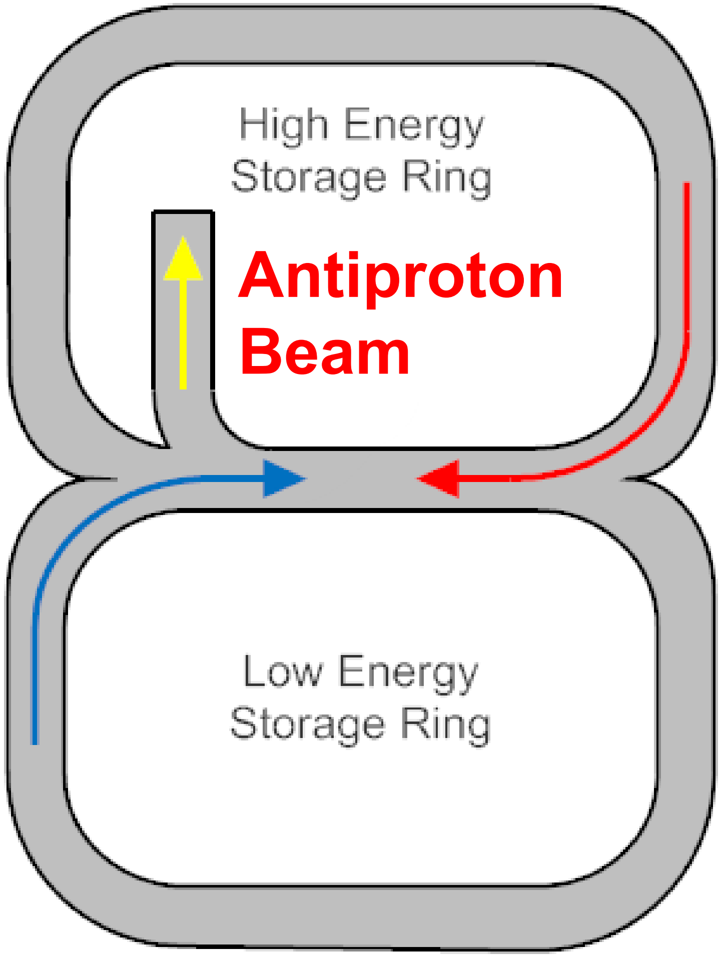
Option 1: Antiproton Production Using a Thin Target

- Instead of using a thick target, the concept is to use a very thin target and have the proton beam pass through it multiple times.
- Alternatively, the “thin target” can be a hydrogen gas jet crossing the proton beam path (existing experimental technique) or a Penning Trap containing protons or ionized molecular hydrogen.



Option 2: Colliding Proton Beams





- Implementation of the above figure would require a **symmetric collider**: 2 proton beams of the same energy
- In order to create a “beam” of antiprotons, there needs to be a net boost in one direction: this requires an **asymmetric collider** with 2 unequal proton beam energies

Projected Antiproton Production Improvement

- In order to antimatter production for deep-space propulsion viable, a **10-fold** increase in production rate is needed.
- Research published at Fermilab in 1994 shows that eliminating the thick target would increase antiproton yield by a factor of 1000x (**3-fold**).
- Instead of using a chain of synchrotrons to accelerate the protons, use a superconducting linear accelerator to gain a **7-fold** improvement.

- **Thin target experiments can be performed parasitically at Fermilab now!**

Projected Antiproton Production Cost

Parameter	Value
Proton Beam Energy during Antiproton Production (GeV)	**1.9**
Desired Antiproton Production Rate (grams/year)	**20**
Price of Electrical Energy [Solar] (USD/kW-hr)	**0.01**
Number of Protons Consumed per Antiproton	**2 x 33**
Number of Antiprotons Generated per Year	1.2E25
Proton Utilization Rate in Collisions (Hz)	2.5E19
Average Total Proton Beam Current (A)	4
Average Proton Power (GW)	7.6
Annual Proton Energy Consumption (kW-hrs)	6.7E10
Ideal Facility Energy Cost (Millions USD/year)	670

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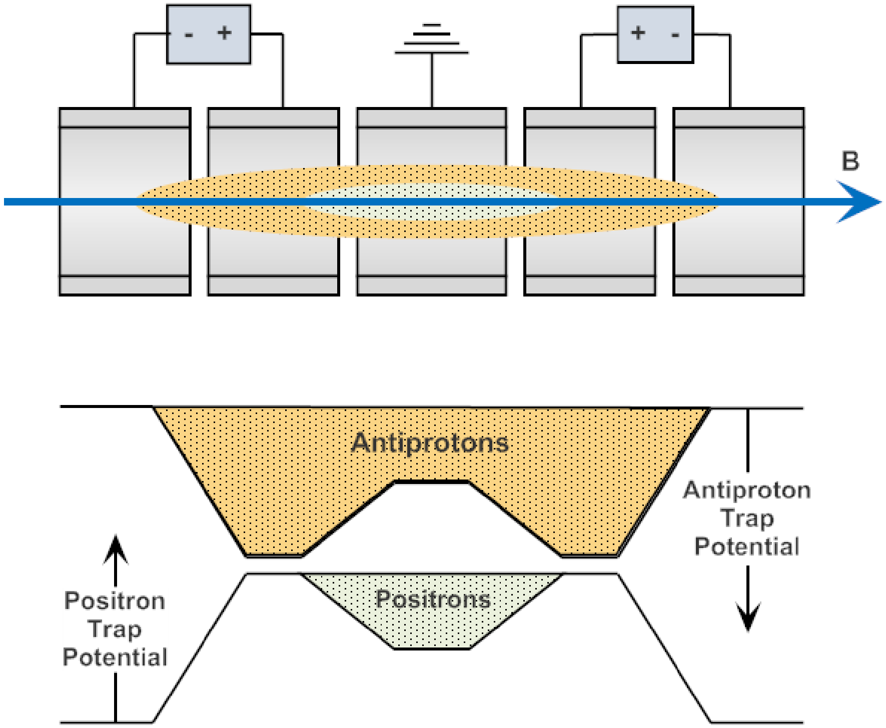
Prior Antimatter Accumulation



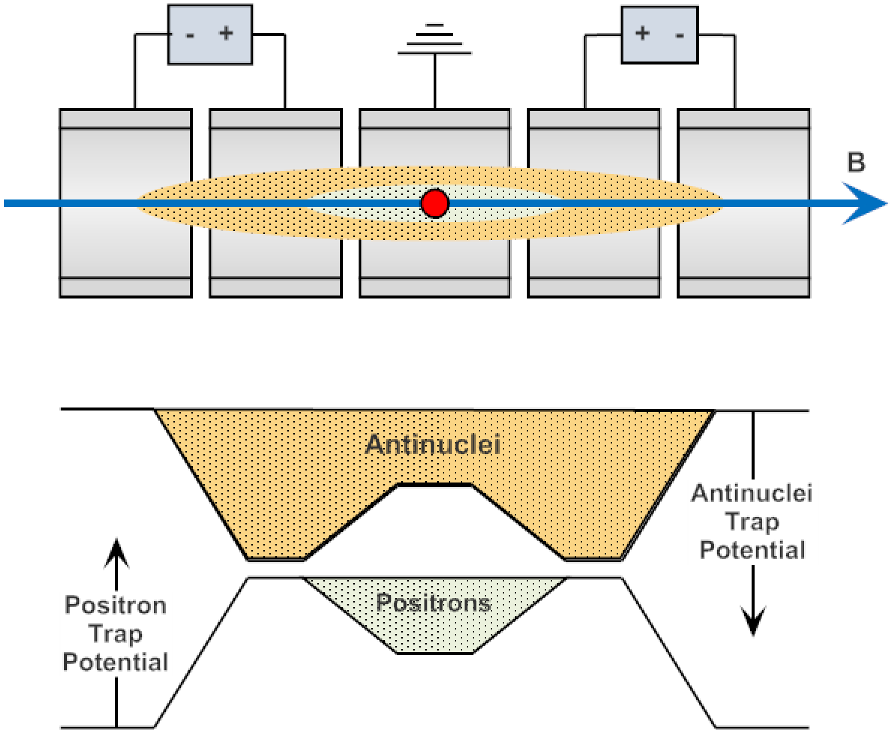
Current antihydrogen production at CERN

- The only conventional way to contain grams of matter is to form neutral atoms
- Neutral antihydrogen has been formed in flight at Fermilab and at rest in CERN
- The production rates are very small due to insufficient antiproton and positron densities

- A different way of looking at the problem is needed
- We know ion bombardment grows mass on a substrate
- We know that electron bombardment can charge an object

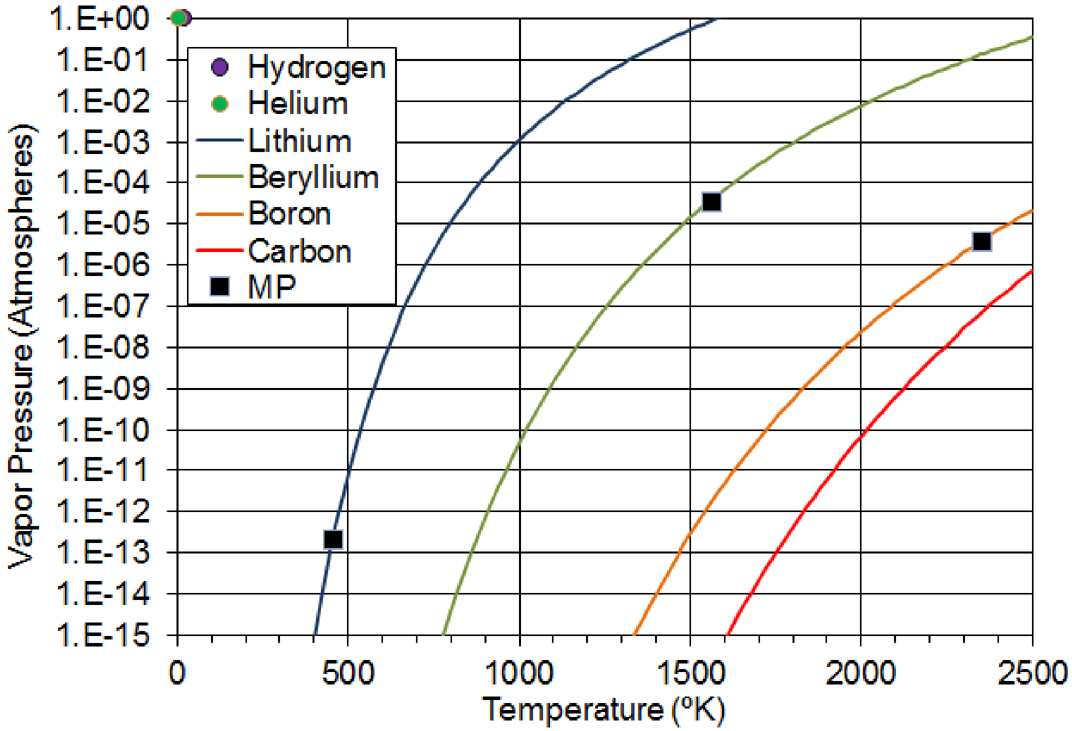
Enhanced Antimatter Accumulation

- Step 1: Levitate a mass of antimatter in the middle of a Penning Trap
- Step 2: Continuously add a stream of antinuclei
- Step 3: Continuously add a stream of positrons (much easier to make than antinuclei).



- Problem: The kinetic energies of the antinuclei and positrons heat up the levitated mass. The only mechanism for heat dissipation is blackbody radiation.

Vapor Pressure of (Anti)Elements

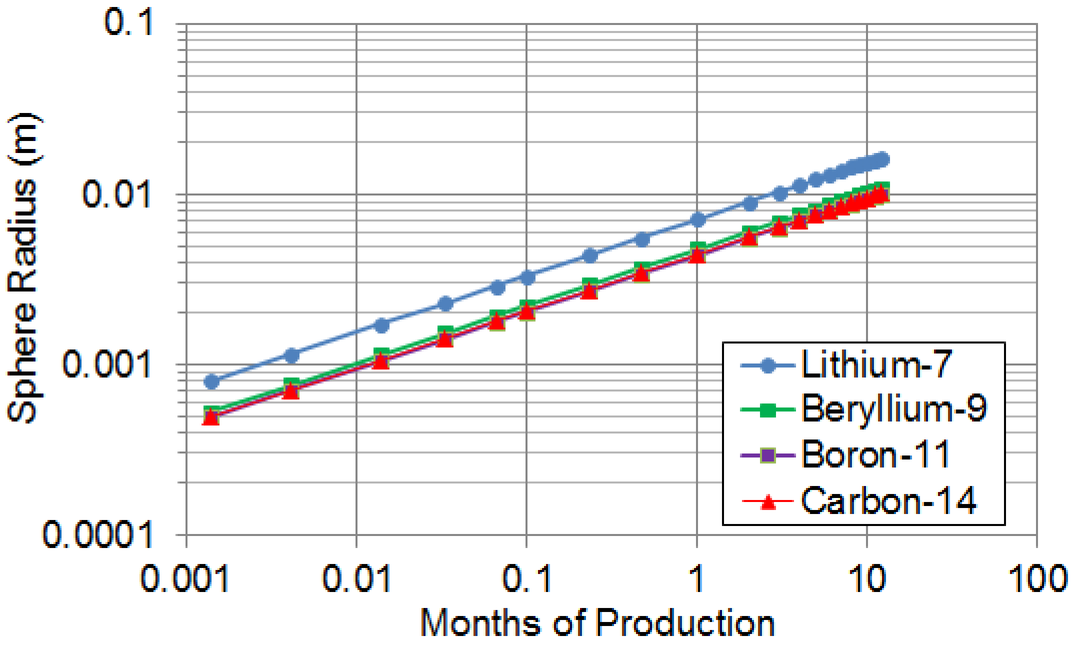


- Hydrogen and Helium are only solid at cryogenic temperatures. They are in the upper left corner of the plot
- The black squares are the melting temperatures
- Lithium has a very low melting point
- Beryllium and Boron are much better, but they are difficult to levitate

- Carbon can be easily levitated and has the highest melting point of any element.

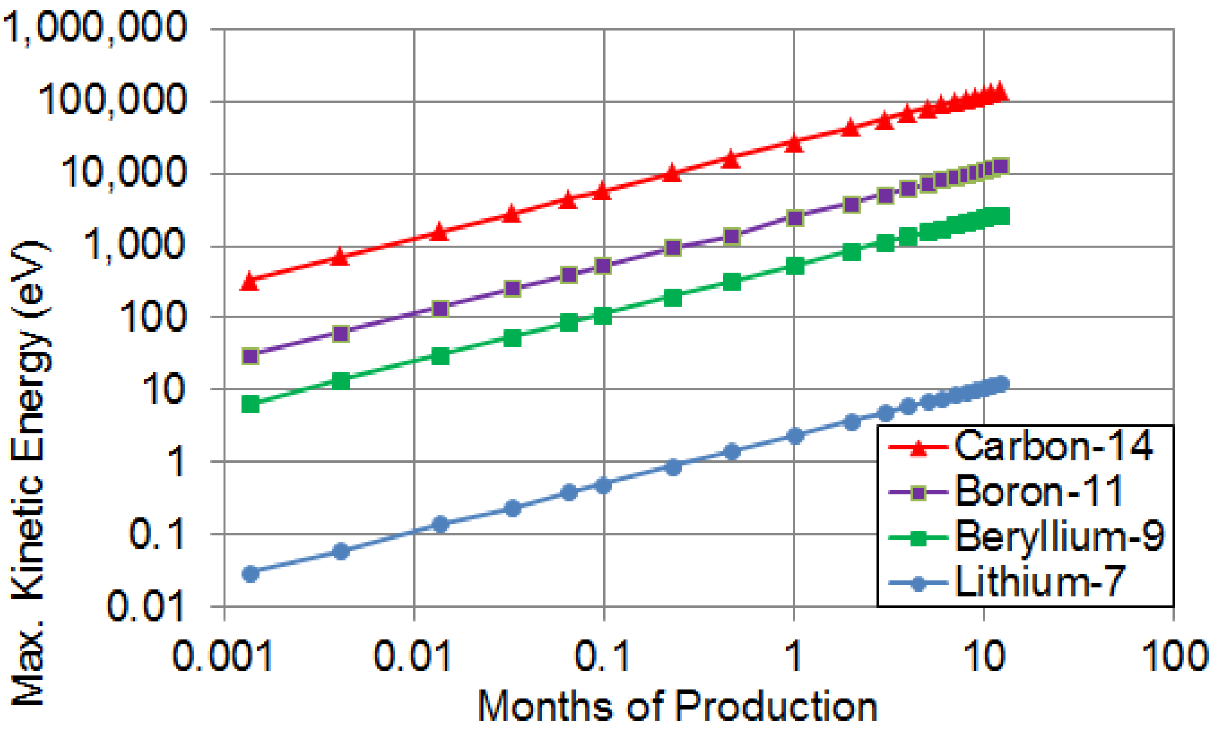
Accumulation Simulation: Radius

- Assume an accumulation rate of 10 grams per year
- Assume the levitated mass is spherical (worst case scenario)
- Assume the initial mass is one hour of accumulation, accumulate for one year



- Simulate the elements Lithium, Beryllium, Boron, and Carbon using their known emissivities
- Initial experiments can be performed using normal matter

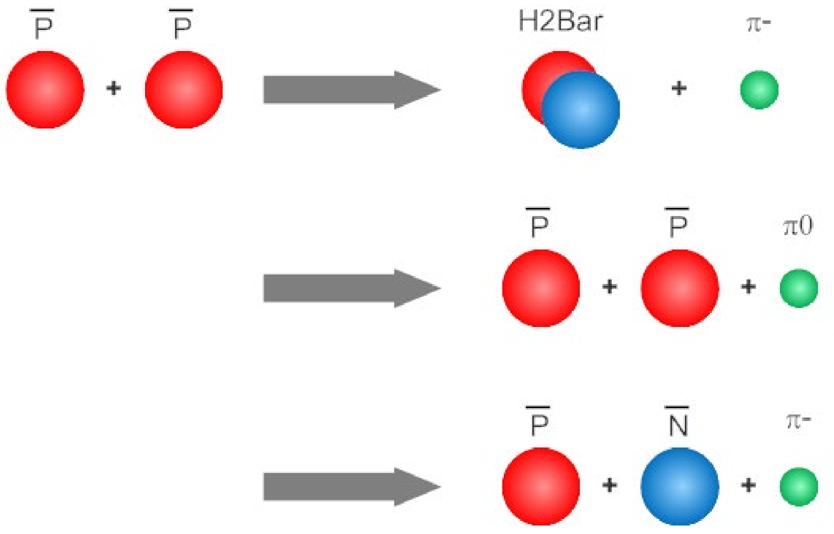
Accumulation Simulation: Radius



- Limitation 1: Melting Point
- Limitation 2: Sublimation Rate

- Assume both beams (antinuclei and positrons) have equal kinetic energy when striking the levitated mass
- Lithium is limited to kinetic energies that are not viable
- Lithium Hydride (LiH) has a melting point of 962ºK

Antinucleosynthesis: Antineutron Production

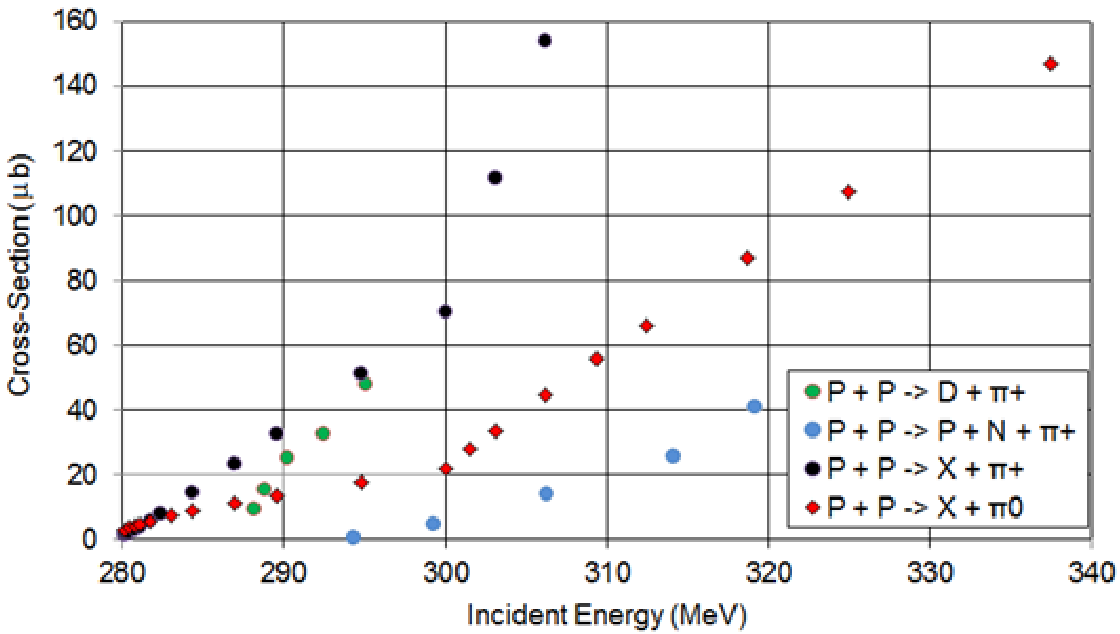


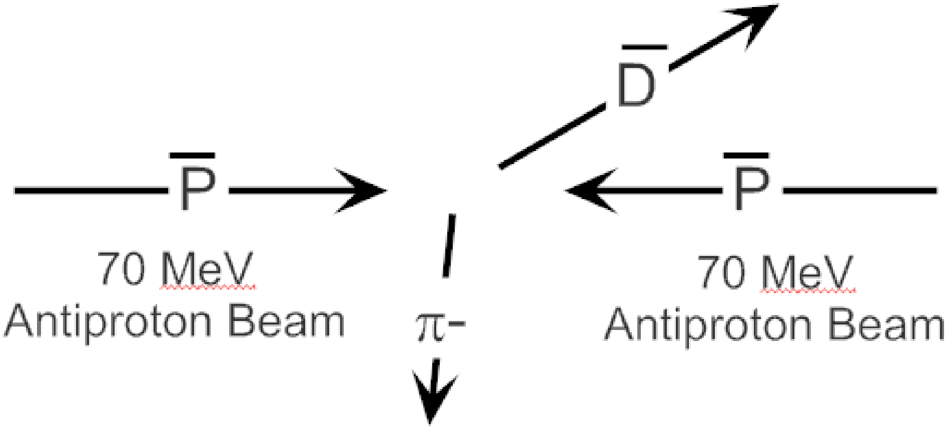
H2Bar is an antideuteron

- For any element above hydrogen, neutrons are needed
- Free antineutron production is useless: they cannot be constrained
- Need to produce antineutrons already bound to antiprotons
- The solution: collide two antiproton beams to produce antideuterons
- Problem: there are other production channels that lower mass efficiency

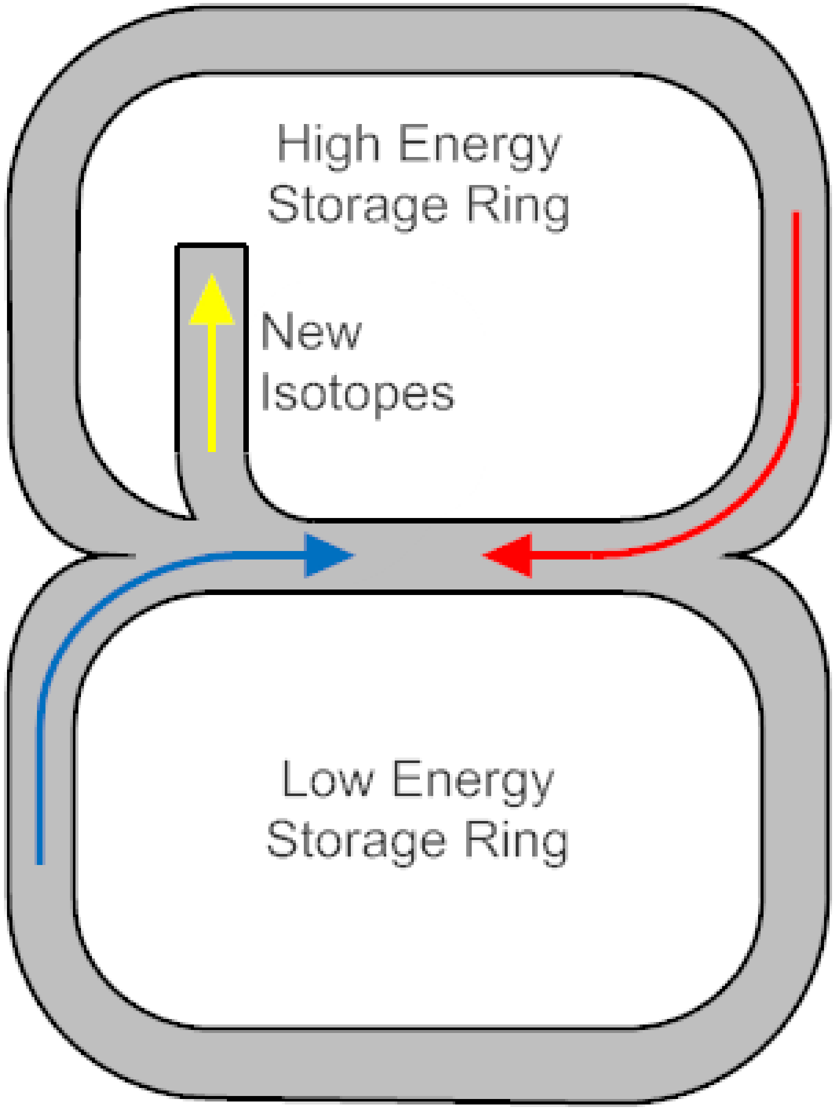
Antinucleosynthesis: Antideutron Efficiency

- The plot shows the probability (cross-section) of a given reaction as a function of kinetic energy of a proton beam striking a hydrogen target
- **80% of the time an antideuteron is formed by colliding to antiprotons**





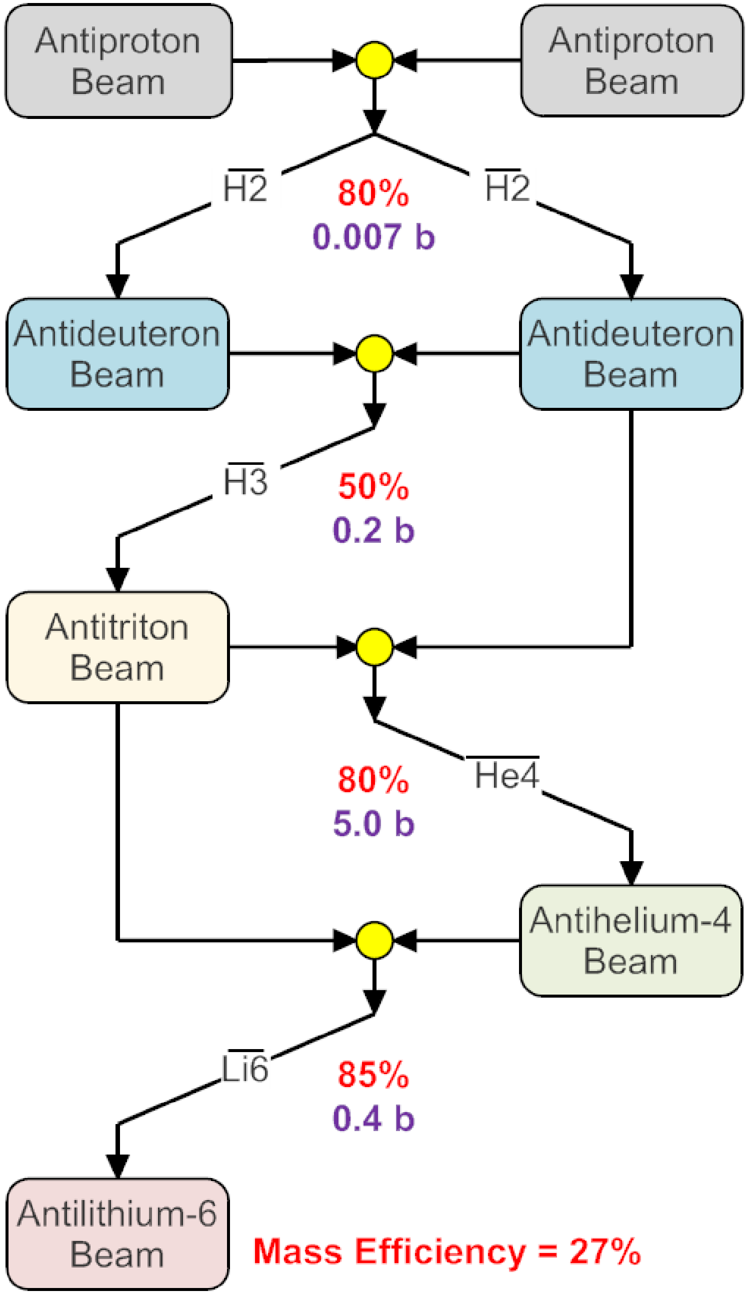
Antinucleosynthesis: Antideutrons & Beyond



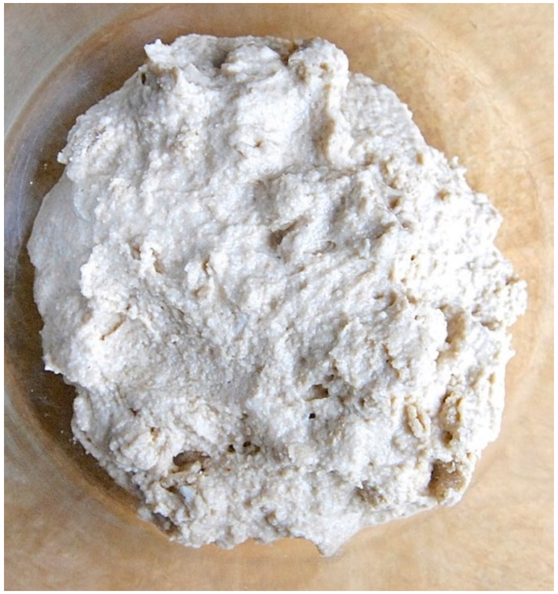
- By colliding two antiproton beams of dissimilar energy (asymmetric collider), a beam of antideuterons is formed.
- **The same architecture can be used for higher mass antinuclei**

Antinucleosynthesis: Antimatter Factory

- Since antilithium will be such a small fraction of overall antimatter mass, low-yield antilithium production channels can be used
- By allowing more mass loss due to free antineutron formation, higher probability collisions can be used
- Even a 27% antimatter mass efficiency for high-rate antilithium formation yields an overall theoretical antimatter production efficiency of 99%



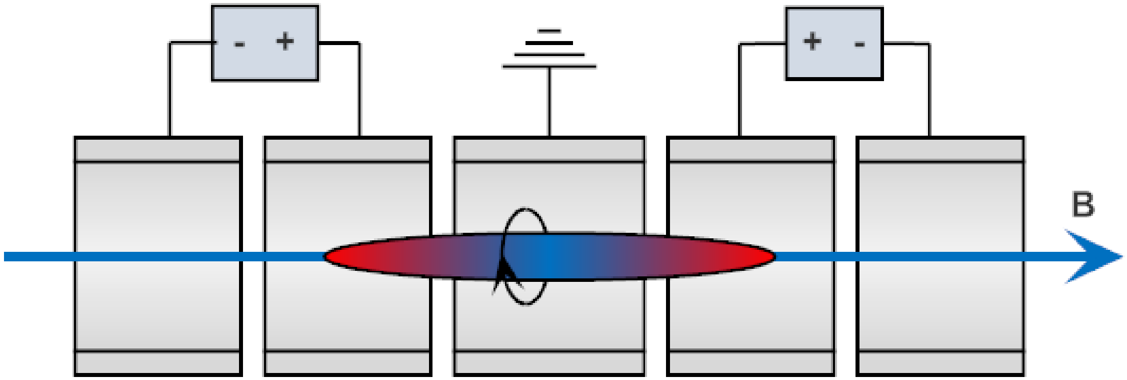
Antinucleosynthesis: Cheating ???



- If you were paying attention, you would have noticed that the accumulation of antimatter mass started at an 1-hour mass (1 mg)
- **Where does this mass come from?**

- Analogy: Sourdough bread production
- The yeast culture used to grow the dough is the original culture used for over 100 years
- Step 1: Grow the mass by adding flour and water
- Step 2: Break off enough for a batch of bread
- Step 3: Repeat Step #1

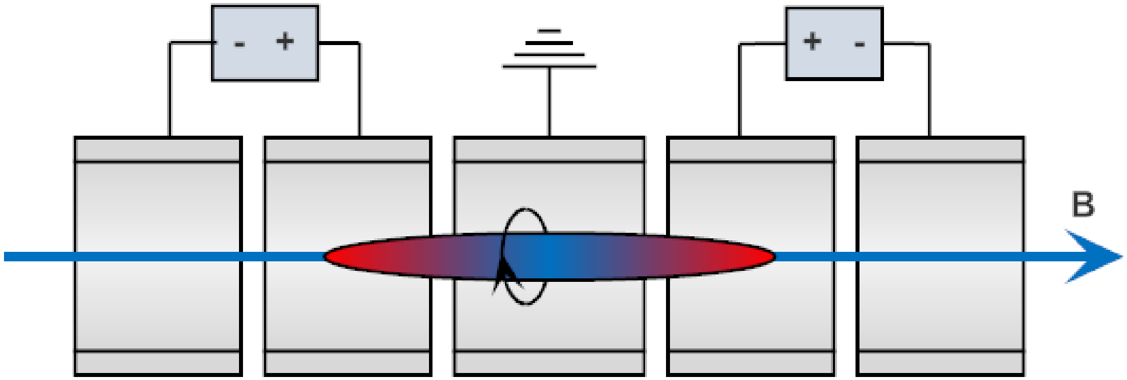
Antinucleosynthesis: Starter Mass



- The levitated mass can be spin stabilized using known “rotating wall” techniques

- Most of the nuclei will be deposited on the ends, causing the levitated mass to become cylindrical in shape
- Once enough antimatter has been accumulated, a laser can be used to cleave off one end to be used as the starter mass for another accumulation cycle.
- This process can be repeated indefinitely
- The creation, growth, and cleaving of a normal-matter mass of carbon is an early and inexpensive experiment.

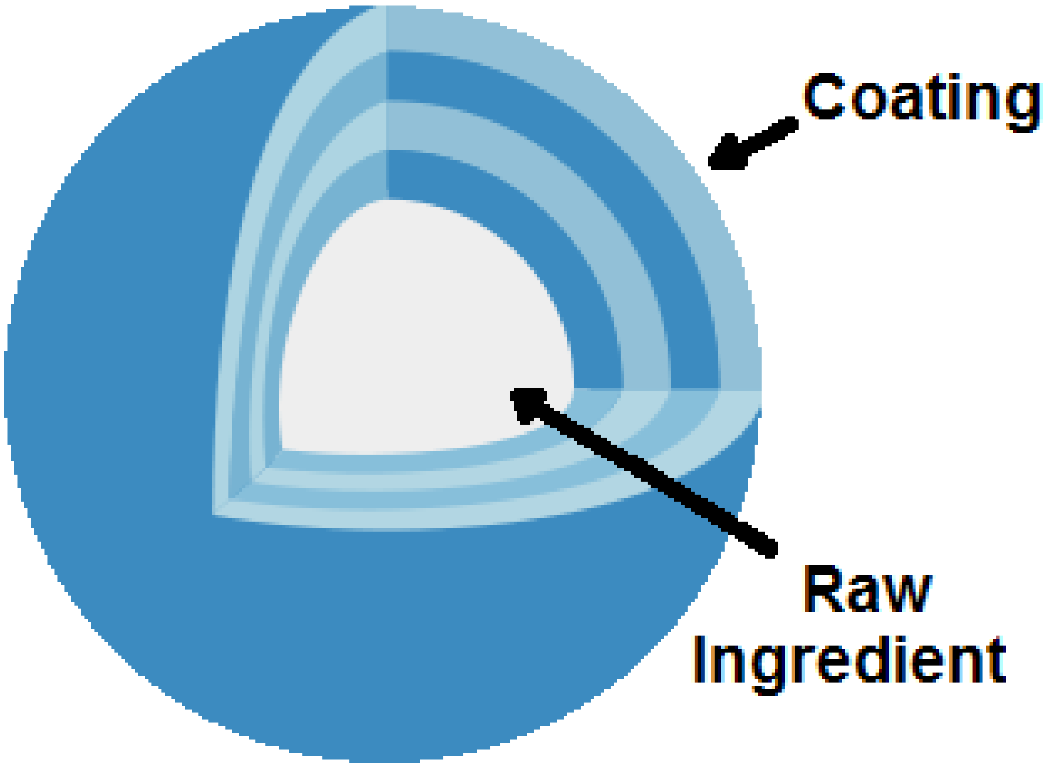
Antinucleosynthesis: Starter Mass



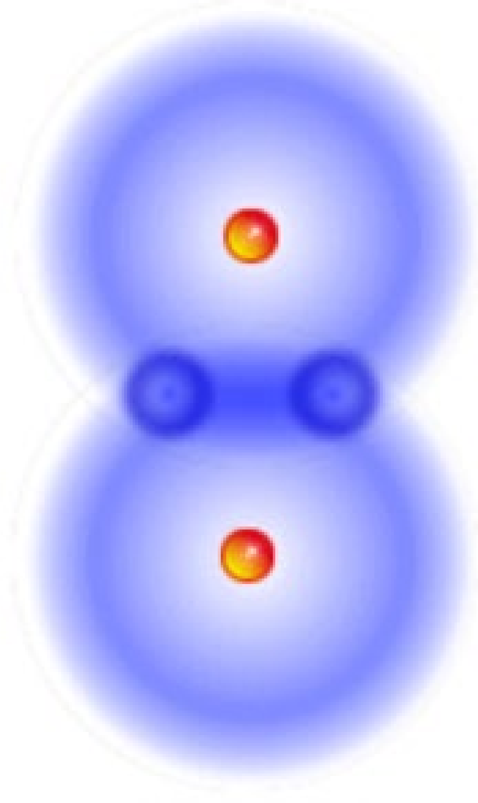
- The levitated mass can be spin stabilized using known “rotating wall” techniques

- Most of the nuclei will be deposited on the ends, causing the levitated mass to become cylindrical in shape
- Once enough antimatter has been accumulated, a laser or electron beam can be used to cleave off one end to be used as the starter mass for another accumulation cycle.
- This process can be repeated indefinitely
- The creation, growth, and cleaving of a normal-matter mass of carbon or LiH is an early and inexpensive experiment.

Antihydrogen Storage



Antihydrogen Storage Problem: Sublimation



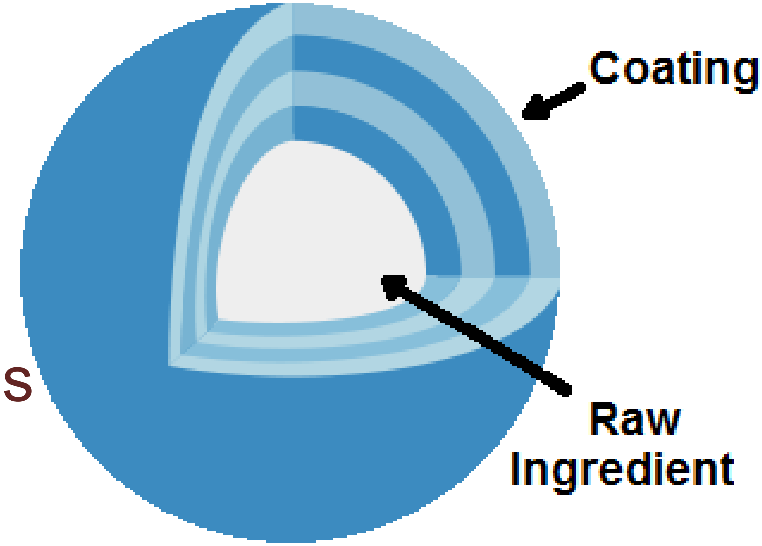
- Isolated antiprotons repel each other electrostatically
- For grams of antimatter, one needs to form molecular antihydrogen
- The vapor pressure of molecular (anti)hydrogen is very high, even at milli-Kelvin temperatures
- Sublimation makes simple antihydrogen storage for 50 years impossible
- Sublimation occurs when vapor pressure is higher than the background vacuum
- The background vacuum needs to be very good to prevent premature annihilations with background gas

Antihydrogen Storage Problem: Sublimation

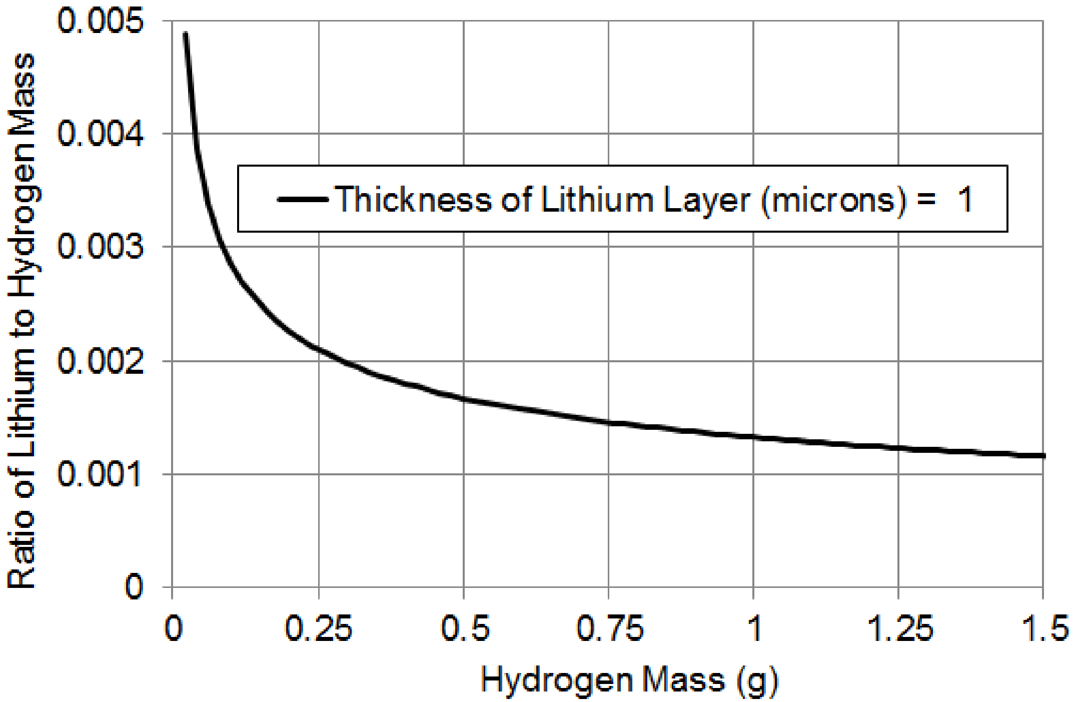
- Use a small amount of **antilithium**
- We came up with this solution in 2018 while writing a NIAC proposal

- Analogy: Vitamin fortification of foods!!!
- Prevents flavor and consistency changes in the fortified foods by preventing chemical reactions

- Step 1: Grow hot anti-H2 molecules
- Step 2: Form anti-H2 snowballs
- Step 3: Coat snowballs with a thin layer of antilithium



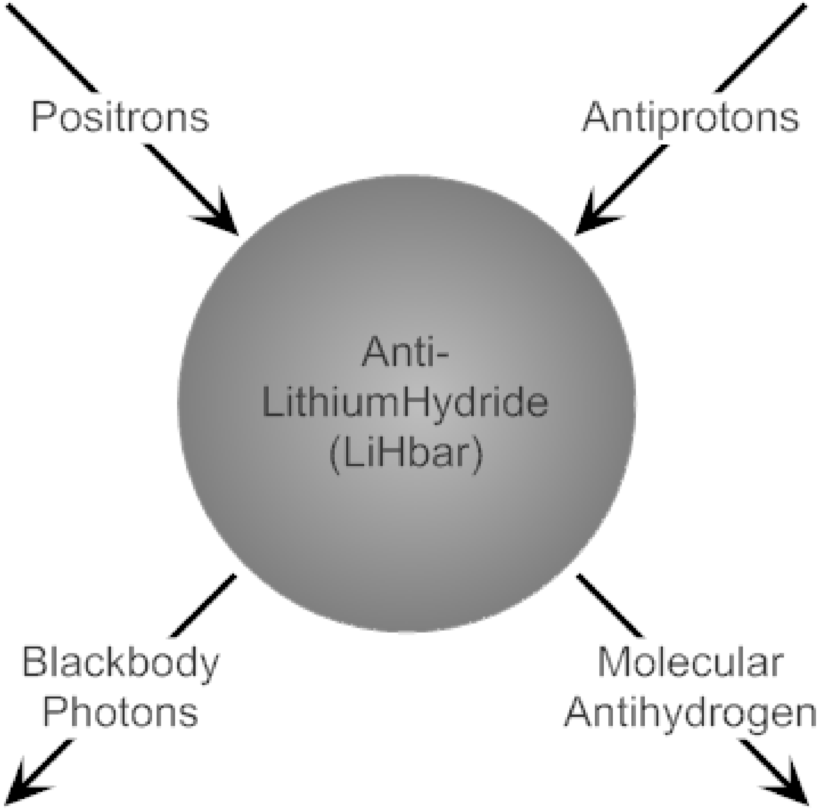
Antilithium Encapsulation



- Initial estimates suggest that a 1 micron layer of lithium prevents the sublimation of cryogenic hydrogen
- Even a 27% antimatter mass efficiency for high-rate antilithium formation yields an overall theoretical antimatter production efficiency of 99%

Step 1: Form Hot Anti-H2 Molecules

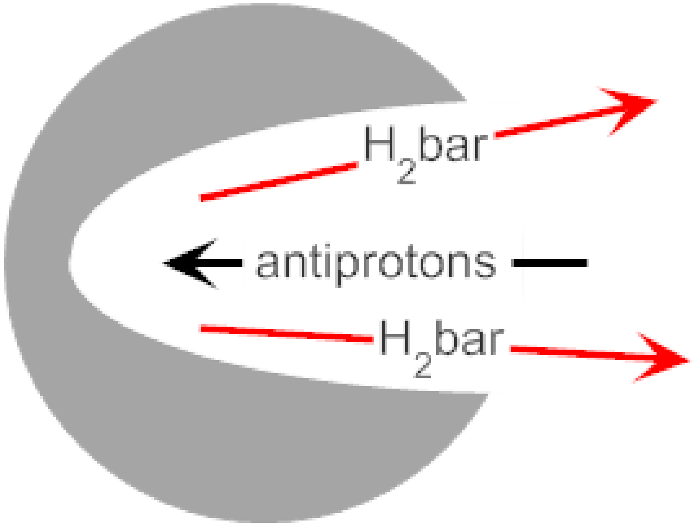
This method is theorized to be the dominant mechanism by which molecular hydrogen is formed in the galaxy (carbonaceous dust).



1. Direct antiprotons and positrons at an anti-LithiumHydride target (might start off as a small antilithium target)
2. Antiprotons pick up a positron within the target and stick with a combination of physisorption and chemisorption
3. Molecular antihydrogen is emitted from the surface
4. Target temperature moderated by thermal blackbody radiation

Step 2: Form an Anti-H2 Snowball

1. Shape and orient the levitated anti-LithiumHydride target so that thermal antihydrogen molecules are emitted in a preferential direction
2. Excite the liberated molecules into an excited Rydberg state and focus them into a beam with electric field gradients **OR** ionize the molecules with an electron beam (forming anti-H_2^-) and focus them electrostatically or magnetically
3. Direct the molecular beam into the growing solid antihydrogen mass

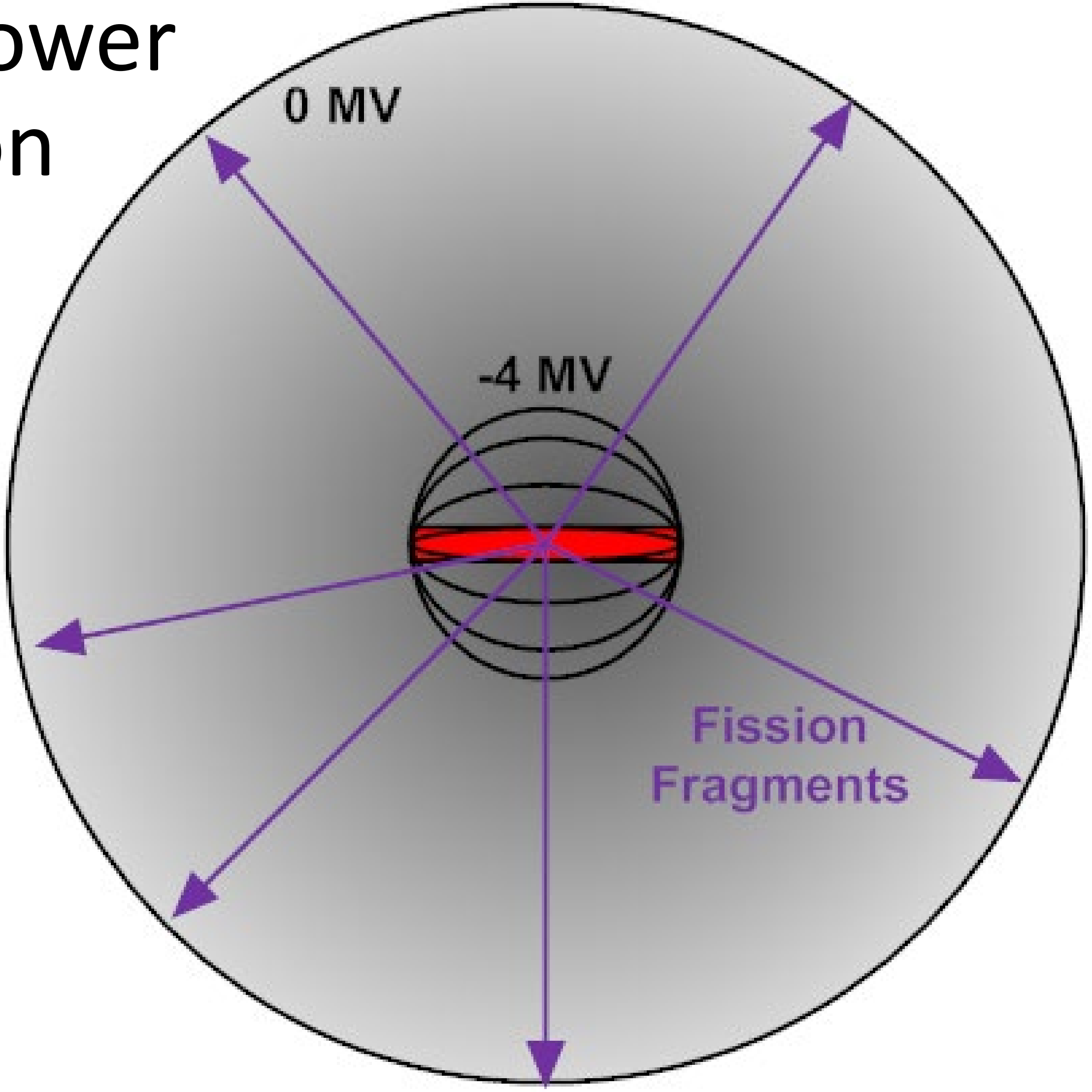


There are many technologies for performing each the above operations … we are currently calculating the efficiencies of each mechanism and putting together an initial experimental method with normal matter.

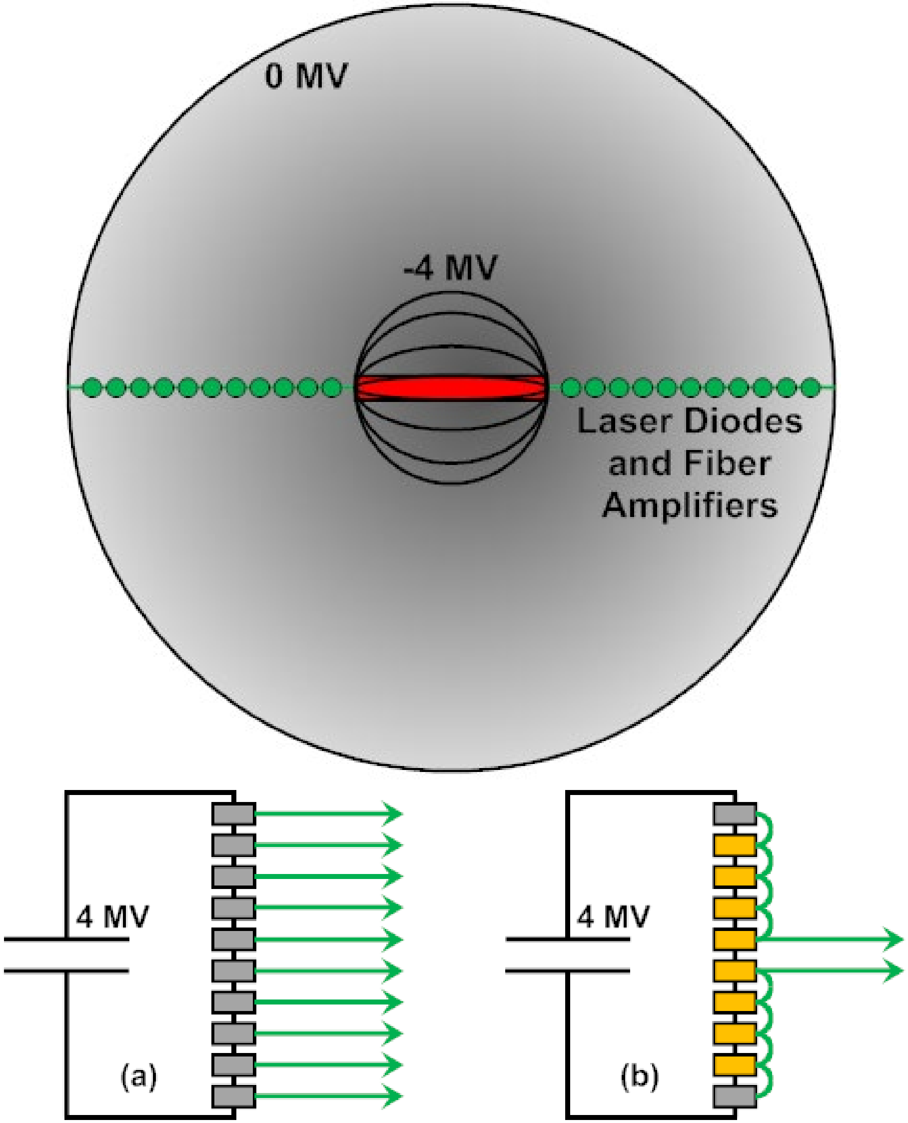
Step 3: Coat the Snowball

- Coating thickness is determined by the sublimation rate of the encapsulated antihydrogen … an easy test with normal matter
- An intermediate layer of lithium hydride will also form
- Cryogenic equipment is too expensive without external funding … instead we have started with sulfur sublimation inhibited with an aluminum coating … an intermediate layer of aluminum sulfide is also expected to form

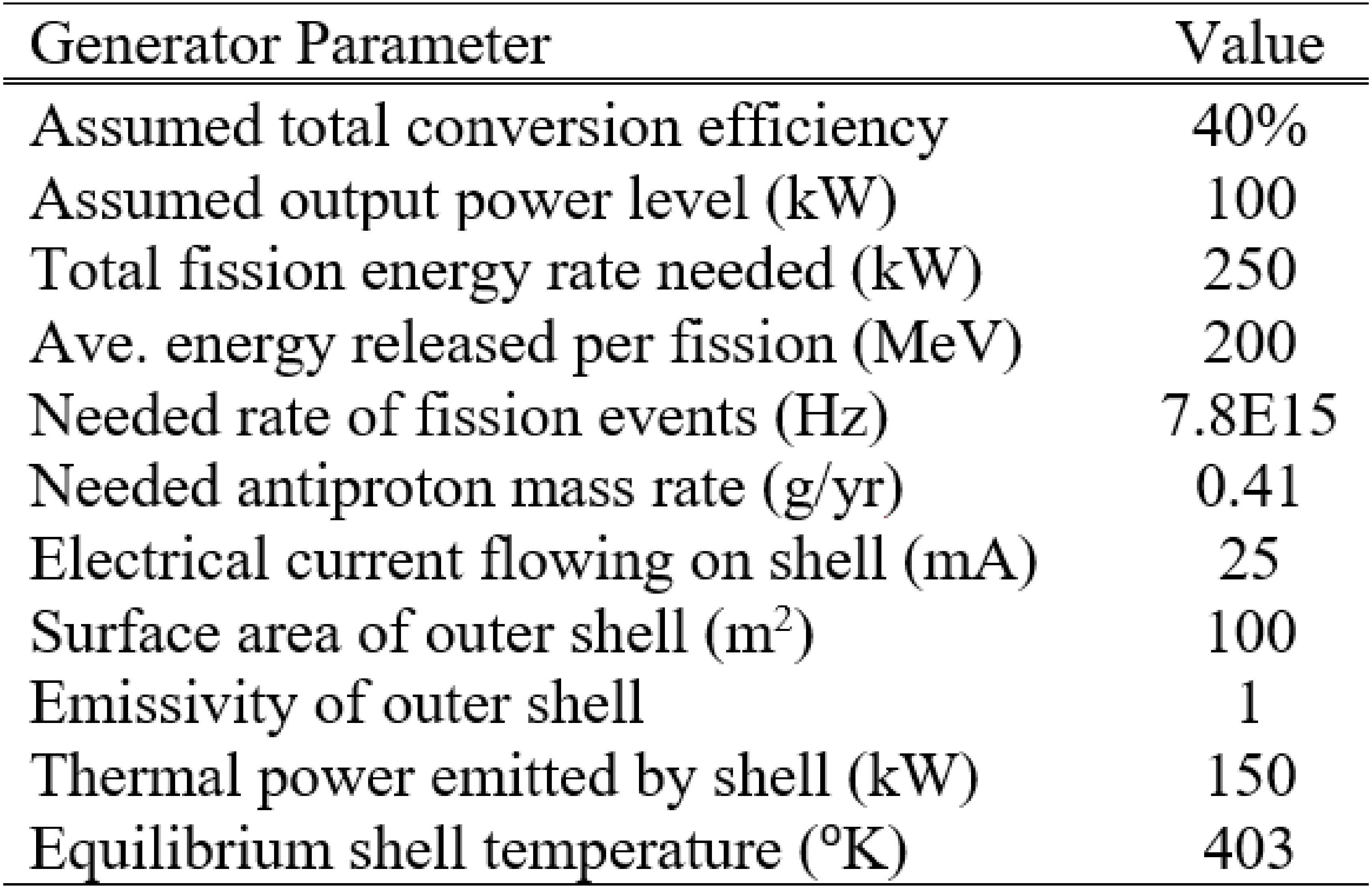
Antimatter-Based Spacecraft Power Generation



Power Generation Architecture



- Fission electrons are very low energy and simple to confine within the inner mesh electrode
- Fission daughters escape to the outside sphere, forming the inner voltage
- Power requires an electrical current … also needed to maintain a desired voltage
- One solution is to use an array of laser diodes and fiber amplifiers



Generator Parameter	Value
Assumed total conversion efficiency	40%
Assumed output power level (kW)	100
Total fission energy rate needed (kW)	250
Ave. energy released per fission (MeV)	200
Needed rate of fission events (Hz)	7.8E15
Needed antiproton mass rate (g/yr)	0.41
Electrical current flowing on shell (mA)	25
Surface area of outer shell (m^2)	100
Emissivity of outer shell	1
Thermal power emitted by shell (kW)	150
Equilibrium shell temperature (°K)	403

Experimental Validation

Am241-source induced secondary emission study on a central “accelerator structure” to simulate annihilation-induced free electrons